The magnetic field in the chromosphere–corona transition zone above a sunspot

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(Submitted September 6, 1982)

Pis'ma Astron. Zh. **9**, 244–249 (April 1983)

RATAN-600 measurements at $\lambda = 2$–4 cm of the magnetic field of a sunspot at the base of the corona are compared with *SMM* satellite measurements for the same spot, using the Zeeman splitting of the ultraviolet C IV line. The radio value, 2100 ± 100 gauss, is about twice the satellite measurement of 1100 ± 300 gauss (at the photospheric level the field strength was 3100 ± 200 gauss). Probably the disparity reflects substantial irregularities in the temperature and density distributions above the spot, as well as the complex field structure at heights about 2000 km above the photosphere.

PACS numbers: 96.60.Pb, 96.60.Na, 95.85.Dj

1. INTRODUCTION

When cyclotron emission was discovered from thermal electrons moving in the corona above sunspots,[1] a new opportunity was afforded for measuring sunspot magnetic fields[2,3] in regions of the solar atmosphere virtually inaccessible to optical observation. Surveys with the RATAN-600 radio telescope have disclosed that the sunspot fields at the base of the corona are only a few tens of percent weaker than the photospheric spot fields and for large spots will often surpass 2000 gauss. Not until lately, however, has this result been verified by independent radio techniques.

On 1980 April 24 the magnetic field strength of a single large sunspot in AR 2394 was measured with the American Solar Maximum Mission satellite. The line-of-sight field component at the center of the spot was found[4] to be 1100 ± 300 gauss, well below the strengths commonly deduced from radio telescope measurements. Aboard the satellite an ultraviolet spectrometer/polarimeter measured the Zeeman splitting of the λ1548 C IV line. As this line is formed in layers whose temperature is $\approx 10^5$°K, the field measurement refers to the transition zone between the chromosphere and the corona — either the same region probed by the radio observations or a region lower down.

In an effort to clarify this disparity we have analyzed RATAN-600 observations of the same active region that had been investigated with the SMM satellite. Our radio estimate for the field strength of the same spot at the chromosphere–corona boundary is 2100 ± 100 gauss. While this is a typical radio value for the field above large spots, it is twice the strength inferred for the AR 2394 spot at the same height from the ultraviolet line. The inconsistency may result from the complex structure of spot fields, which have a strong transverse component even at the center of the spot, or perhaps from thermal irregularities in the transition zone, with isolated hot elements from the corona penetrating into the strong-field region; and to some extent the disparity might also reflect an imprecise setting of the satellite on the position of maximum field strength.

2. RADIO OBSERVATIONS

Our analysis has utilized scans of AR 2394 made with the RATAN-600 on three dates (1980 April 23–25) at four wavelengths (λ = 2.0, 2.7, 3.2, 4.0 cm). The intensity and the circular polarization were recorded (Stokes parameters I, V). Observations were conducted daily with the south sector of the main reflector, using the flat periscopic mirror. At the half-power level the computed dimensions of the antenna beam were 17″×14′, 24″×18′, 27″×22′, 34″×25′ at the four wavelengths. Although other active regions did come within the N-S beam pattern during this period, they were decidedly weaker, and we have neglected their radio emission.

Figure 1 shows the radio scans of the active region (the I, V channels) obtained at the four wavelengths (2.0–4.0 cm) at about April $24^d 09^h 10^m$ UT. These are matched against a sketch (same scale and position) of the spot group (designated No. 212 in the bulletin Solnechnye Dannye), based on a photoheliogram obtained at the High Altitude Astronomical Station in Kislovodsk. The sketch is labeled with the polarity of the individual spots and their field

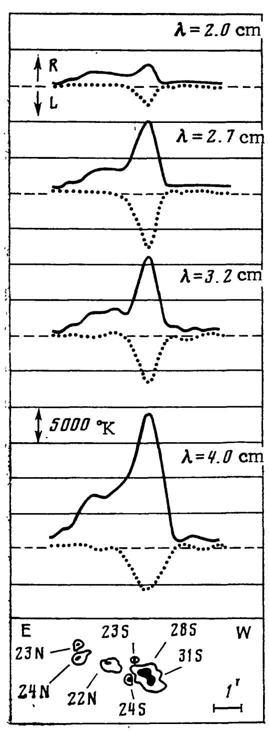

FIG. 1. RATAN-600 scans of the local source associated with the spot group AR 2394, obtained on 1980 April 24. Solid curves, the Stokes intensity parameter $I = \frac{1}{2}(T_a^R + T_a^L)$; dotted curves, the Stokes polarization parameter $V = \frac{1}{2}(T_a^R - T_a^L)$; dashed lines, the level for the quiet sun. Beneath the scans is a diagram of the spot group (same scale) sketched in white light at the Kislovodsk station, indicating the polarity and strength (in 10^2 gauss) of the spot fields.

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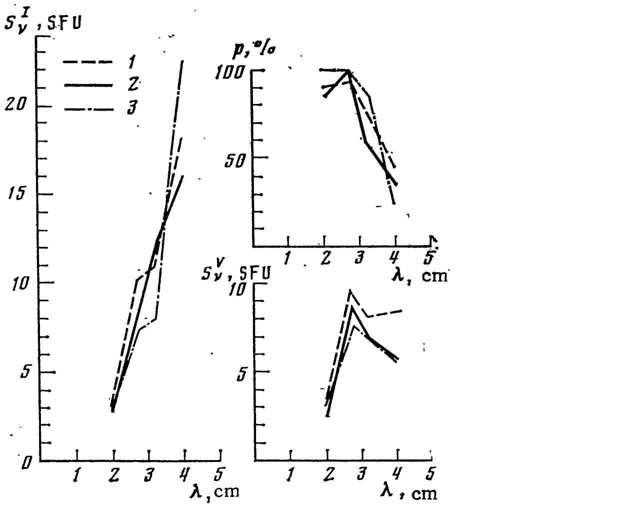

FIG. 2. Spectra for the total and circularly polarized intensities S_ν^I, S_ν^V and the percentage polarization p measured by the RATAN-600 at four wavelengths in the core of the local source associated with spot group AR 2394 on: 1) 1980 April 23; 2) April 24; 3) April 25.

strength in hundreds of gauss. Each scan is accompanied by a dashed line representing the estimated level of the quiet sun. In both the intensity and the polarization channel the radio curves show a prominent peak above the largest spot in the group; in the polarized component this spot contains the bulk of the radio power. The polarization p in the peak approaches 100%.

In Fig. 2 we display spectra for the total flux density in solar flux units, the flux of the circularly polarized component, and the percentage polarization. In Fig. 3 another set of spectra give brightness temperatures for the core of the local radio source, which is situated above the large spot in the group (since the core component cannot be discriminated very accurately, the T_b values may be in error by a factor 2).

3. MEASURED FIELD STRENGTH

The flux rises steeply with wavelength throughout the 2-4 cm range (although there is some evidence for a shoulder at λ = 2.7-3.2 cm). The polarization is near-total at 2.0-2.7 cm but declines sharply toward longer wavelengths. This behavior suggests that coronal bremsstrahlung above the spot does not contribute significantly at all; evidently the dominant factor is the magnetobremsstrahlung or cyclotron radiation generated by the penetration of the strong magnetic field into the hot ($T \approx 10^5$°K) layers of the solar atmosphere. Standard estimate for the optical depth of the corona[1] indicate that the chief contribution to the emission should come from the extraordinary wave at the

TABLE I. Field Strengths Measured above a Sunspot in AR 2394

1980	B, gauss		
	In optical range* (photosphere)	From UV line** (transition zone)	At centimeter wavelengths (transition zone, corona)
23.IV	2800±390	–	2140±60
24.IV	3100±190	1100±300	2110±80
25.IV	3200±190	–	2450±250

*Field measurement errors from Stepanyan.[5]
**Line-of-sight field component.

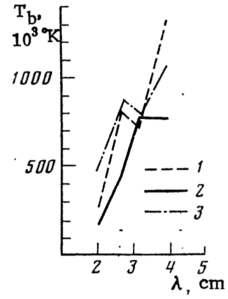

FIG. 3. Brightness-temperature spectra for the core of the local source associated with spot group AR 2394 on: 1) 1980 April 23; 2) April 24; 3) April 25.

third harmonic of the gyrofrequency, and from the ordinary wave at the second harmonic. One may infer that the 2.0-2.7 cm emission represents primarily the third harmonic (the sign of the polarization corresponds to the extraordinary wave), but that beginning at 3.2 cm, where p falls below 100%, the contribution of the ordinary wave generated at the second harmonic of the gyrofrequency becomes important as well.

For the third and second harmonics the field strength depends on wavelength as

$$B = 3570\ \lambda^{-1}\ \text{gauss}\ (\omega = 3\omega_H), \quad (1)$$

$$B = 5355\ \lambda^{-1}\ \text{gauss}\ (\omega = 2\omega_H) \quad (2)$$

(λ in centimeters). The fact that cyclotron radiation is definitely present even at λ = 2.0 cm indicates that at the base of the corona the field B > 1800 gauss. The second-harmonic ordinary-wave emission at $\lambda \approx 3$ cm gives practically the same estimate for the field strength [Eq. (2)].

One can evaluate the field strength more accurately by measuring the limiting (shortest) wavelength λ' of the highly polarized radiation from the core of the source. In our case a direct measurement is not available: λ' clearly is shorter than 2 cm and lies beyond the range covered by our observations. However, the experience gained in measuring magnetic fields by the gyroresonance technique[3] demonstrates that it is realistic to extrapolate the spectrum linearly to the level of zero radiation.

In order to assess how much error the extrapolation might introduce into the result, we have tested eight different versions of the method, expressing the spectrum of the radio-source core both in solar flux units and in terms of the peak antenna temperature, using both linear and logarithmic wavelength scales. The results obtained for the field strength (mean value with rms deviation for all versions combined) are given in Table I, together with the photospheric field quoted in Solnechnye Dannye and the satellite measurement from the Zeeman splitting of the ultraviolet line.[4]

The radio estimate B = 2110 ± 80 gauss obtained for April 24 amounts to 68% of the photospheric estimate and is nearly twice the line-of-sight field component derived for the transition zone above the center of the spot from the observations with the american SMM satellite.

4. DISCUSSION

The high value we have obtained for the field strength above a spot at the base of the corona is a typical result in our series of radio observations.[6,3] Estimates derived from measurements with large aperture-synthesis arrays,[7,8] similarly relying on analysis of cyclotron radio emission, have yielded values B = 600-900 gauss at coronal levels above sunspots, but these observations lack data at shorter wavelengths, so that in principle one is precluded from measuring the stronger fields.

Some years ago Livshits et al.[9] pointed out that above sunspots the corona ought to "sink down" to the level of fields $B \approx 1200$ gauss. Their reasoning was based on solar eclipse data at $\lambda \approx 3$ cm available at the time. Subsequent eclipse observations[10] indicated that above large spots cyclotron radiation is emitted even at $\lambda = 2$ cm, implying that fields as strong as $B \approx 1800$ gauss develop in the hot coronal or subcoronal layers.

Thus a variety of observational evidence for the cores of local radio sources above sunspots suggests that strong (1000-2000 gauss) fields can penetrate into the hot ($T = 10^5$-10^6 °K) regions of the solar atmosphere. It remains a puzzle as to how radio observations can give a field strength twice as high as deduced for the same spot from the Zeeman splitting of the ultraviolet C IV line. Several possible explanations come to mind.

a. The radio measurements give the total field strength, while the satellite observations yield only the component along the line of sight. Since the spot was located near the center of the solar disk at the time of measurement and the ultraviolet spectrometer/polarimeter was set on the center of the spot, one would think that the longitudinal field component should practically coincide with the total field vector. But there are some indications[11] that even at the photospheric level, sunspot fields may have a strong transverse component associated with the complex magnetic field structure, which is by no means vertical even close to the center of a spot.

b. Ultraviolet and x-ray data provide independent evidence that the solar atmosphere above subspots is subject to severe temperature nonuniformities. If along some magnetic flux tubes the transition zone were to lie at a comparatively high level and be fairly thick, while along others the corona were to sink lower down and the transition zone were to be very thin, then in terms of that inhomogeneous model the radio values for the field strength might refer to hot volume elements located at lower levels, and their fields naturally ought to be stronger, just as we observe.

c. The UV spectrometer/polarimeter was set by ground command upon the "center" of a sunspot having a rather intricate configuration, curved and elongated, rather than upon the position of peak field strength. On the other hand, the radio data, acquired by scanning the whole spot, serve to establish the peak field in the hot atmospheric layers above the spot.

Probably none of these factors alone can account for the two-fold disparity in the estimated field strengths, but jointly they might be able to explain the situation. At the same time our discussion makes it clear that if we are to understand the structural behavior of the solar atmosphere in the corona and transition zone above a sunspot, it will be essential for high-resolution radio data to be analyzed concurrently with magnetometry in other parts of the spectrum.

Grateful thanks are due to Sh. B. Akhmedov and A. N. Korzhavin for valuable suggestions and comments which the authors have borne in mind in carrying out this investigations.

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